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Research Article

Twin-Double Layer Structure Producing Tailward Ion Jets in the Earth's Magnetosphere

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Abstract

This paper investigates the generation, expansion, propagation and distribution of anti-sunward plasma ion jets and energetic particle populations in the nightside magnetosphere. An electrical circuit model with passive components is defined to set up a new ***twin-double layer (DL) entity*** in the near Earth's magnetotail. A locally, thinned plasma sheet is potentially transformed to ***a positively charged cavity***, while in two areas adjacent to this cavity northern and southern boundaries, ***two distinct strong DLs*** are constituted forming a structure with three layers. The ions with gyroradii comparable to the local magnetic field curvature are effectively trapped in this cavity. The neutralizing electrons flow into the cavity and establish the two DLs in a symmetrical arrangement with respect to the neutral sheet. Although the overall layered structure is neutralized, however, three distinctly charged layers are developed. The electrons set up an oscillatory motion perpendicularly to the neutral sheet and along the magnetic field lines. In this metastable state, the ions that abide at the tailward edge of the cavity are electrostatically repelled ***yielding an anti-sunward plasma ion jet in form of a current moving orthogonally to the magnetic field lines*** and over the neutral sheet. Furthermore, ***since the twin-DL entity is treated as a part of a huge magnetospheric circuit that comprises a large inductance, it is potentially explosive***. In its explosive mode, the circuit is able to accelerate charged particles reaching energy levels of hundreds of keV. The latter is a property of the circuit; ***a cross-scale coupling is effectuated in the Earth's magnetotail through the circuit current.*** Therefore, the proposed circuit model with the twin-DL structure reveals ***the physical mechanism producing the electromotive force (for the intra-magnetosphere dynamo) for generating the current flow in the Boström's type II circuit.*** An indicative case study incorporating *in situ* Geotail-Satellite datasets supports the new concept's validity. The proposed model is also able to explain why and how an ion jet is generated forming a pseudo-magnetic flux rope (MFR) shaped structure tailward of the twin-DL entity; ***the new approach assumes that the pseudo-MFR structure is explicitly coupled with the ion jet current launched by the twin-DLs.***

Keywords: Plasma sheet, magnetic reconnection, double layers, magnetic flux rope, field-aligned currents

1. Introduction

This work applies the plasma double layer (DL) theory to suggest a promising mechanism explaining the ion jets and energetic particle populations in the Earth's magnetotail. An impartial approach to this complicated topic would be highly recommended; in this very crucial area of space plasma physics a multitude of questions remain unresolved. Any new concept is legitimate and the whole scientific community would further test it. Certainly the truth is not subjected to the law of majority.

Apparently, we shall not try to criticize the reconnection mechanism, as it was done (for instance in the past) by Alfvén [1, 2] and recently by Scott [3] who lines up with Alfvén's arguments. At the present time, we know that ***the magnetic reconnection is considered the dominant and fundamental physical process occurring in a magnetized plasma***, whereby magnetic field lines are effectively broken and connected, resulting in a change of magnetic topology, conversion of magnetic field energy into bulk kinetic energy and particle heating. Magnetic reconnection (supposedly) directly converts magnetic energy into kinetic energy in the form of bidirectional plasma jets. Clearly, Baker [4] introduced a model of an X-type magnetic line, in the Earth's magnetotail, potentially producing energetic particles of many hundreds keV. However, for instance Gosling et al. [5] examined energetic particle data in Petschek-type reconnection exhausts in the solar wind without evidence for any substantial increase in energetic particle intensities. They concluded that "this indicates that ***local reconnection is not a significant source of energetic particles in the solar wind*** and suggests the possibility ***that reconnection itself may not be a particularly effective process*** for populating other space and astrophysical environments with energetic particles". Critical issues on magnetic reconnection in space plasma can be found in the review work of Lui et al., [6]. It is well known that Alfvén was explicit in his condemnation

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of the reconnection concept. He characterized it as an "erroneous concept" and the relative magnetospheric and solar wind physics as a "pseudoscience". The crucial difference between the two explanations is the question of which quantity (time-varying electric current or moving magnetic field "lines") causes energy release from the magnetized plasma [3]. At the present time, the most popular model for magnetospheric substorms, the near Earth neutral line (NENL) model, is actually based on the X-type reconnection line [7, 8].

In our approach which is analytically exhibited in the next section, we argue that (paradoxically) ***it is not impossible net positive charge to be produced in a thinned current sheet (TCS)***, since the inflowing electrons finally set up an oscillatory motion perpendicular to the current sheet. The chaotically moving ions are effectively trapped in the TCS creating a positively charged cavity, whereas the neutralizing electrons finally form two DLs, at the northern and southern boundaries of the cavity. The existence of positive charge, at the tailward edge of "the cavity", potentially produces an ion jet. Electrostatic forces and electric fields parallel to the magnetic field lines are essential to the proposed mechanism. Moreover, it can be assumed that ***the current carrying DLs are exposed to explosive processes*** being able to accelerate particles to extremely high energies and to generate plasma beams with very high velocities.

Certainly, the energetic particle fluxes in a plasma sheet represent a very small fraction of the total particle population. From systematic research efforts [9], we know that the 200 keV energetic proton differential fluxes are 4-5 orders of magnitude lower than those of 30 keV. In the auroral regions double-layer structures were observed by Boström [10] using the Swedish Viking satellite which have scale lengths of about 100 m and where the plasma density is reduced by up to 50%. However, in the Earth's magnetotail, we do not have any evidence for existing DLs.

2. The twin-DL entity, fundamental consequences

2.1. Surplus of positive (and negative) charge in a TCS

In a thinned plasma sheet the chaotization of ion orbits begins when R_c is about 9 r_g; the full chaotization is achieved at the limit $R_c = r_g$, where r_g and R_c are the ion gyro-radius and the curvature radius of the local magnetic field lines, respectively [11]. Their findings explain, without any assumption of wave-particle interaction, rather different properties of particle dynamics in a two-dimensional magnetotail-like field reversal and of dynamics of a collisionless plasma in it. Certainly, the electrons under these conditions are not demagnetized; they perform their adiabatic motion as previously. When $R_c > 9\ r_g$, the ion entry rate into the plasma sheet (over the meridional plane) is equal to the ion exit rate out of the plasma sheet. Conversely, under the geometric condition $r_g \leq R_c < 9\ r_g$, the ions may lose their initial orbits and, consequently, slow down their velocities or even become temporally trapped within the thinned current sheet (TCS). Therefore, ***an ion accumulation process begins which builds up positive charge*** with potential serious consequences for the plasma sheet dynamics. The above geometric condition is rather frequently satisfied near the Earth and during magnetospheric substorms, when the plasma sheet thickness is measured to be ~ 2000 km [12] and the r_g may have the typical value of ~ 400 km. In parallel, as the positive charge accumulates and the ion density increases, ***an electron current will immediately flow toward the positive charge neutralizing it***. The surplus of positive (negative) charge is (from now on) denoted by Q^+ (Q^-). Parenthetically, it should be noted that a portion from the Q^+ ions, that move at random, will certainly be subject to pitch angle scattering and will finally precipitate into the ionosphere. As we shall argue later on the magnetotail region characterized by $r_g \leq R_c < 9\ r_g$ is acting like an ion donor in a p-type semi-conductor; it is termed "akis structure" by Sarafopoulos [13-15].

2.2. Double layer formation mechanism

During the Q^+ accumulation process within the locally thinned plasma sheet, two layers with different plasma properties would be created at the two boundary regions (close to the northern and southern plasma sheet); therefore, ***two double layers (DLs) symmetric with respect to the neutral sheet are consequently formed.*** We bring into play here the typical processes taking place in a plasma divided into two regions by a plane and the one region has a higher electron density than the other side. In this situation, the electrons may stream freely in either direction and the flux of electrons from the dense plasma to the low density plasma will be greater than the flux of the electrons from the low density plasma to the dense plasma. Because many more electrons enter the low density plasma than exit it, part of the low density region becomes negatively charged. The dense plasma, conversely, becomes positively charged. Therefore, ***an electric field builds up***, which starts to accelerate electrons towards the dense region, reducing the net flux. In this way, the electric field builds up until the fluxes of electrons in either direction are equal, and further charge build up in the two plasmas is prevented; a DL is formed. ***In the Earth's magnetotail we shall have two DLs, one at each hemisphere***, as it is schematically shown in Fig. 1. Moreover, in this context we can infer that the DL electric field is going to build up as far as new ions can enter into the central dense region; a demand that is satisfied when the ion thermal energy is higher than the DL potential drop (Φ_{DL}). If a balance is achieved, ***the potential drop will be equal to the ion thermal energy*** ($e\Phi_{DL} \cong k_B T_i$); consequently, such a double layer is a marginally strong DL. We know that the ion thermal density in plasma sheet is about seven times the electron thermal density [16]. Finally, in a TCS a twin-DL structure will be probably formed within the Earth's magnetotail; each DL is extended in the region where an electric field parallel to the magnetic field lines (E_{II}) is drawn in Fig. 1. Along the X-axis the extent of DL is dictated by the relation $r_g \leq R_c < 9\ r_g$. Within the sketched topology of symmetric DLs, the electron population that is initially accelerated in one DL, will be equally decelerated in the other DL, after crossing the neutral sheet. Therefore, ***the electrons oscillate over the meridional plane and along the magnetic field lines;*** they obtain maximum (minimum) velocities at the neutral sheet (just at the outermost parts of their oscillation displacements). It should be pointed out that in the twin-DL structure (of Fig. 1), ***the overall charge of the ensemble is compensated, even though there are ambipolar electric fields parallel to the magnetic field lines.***

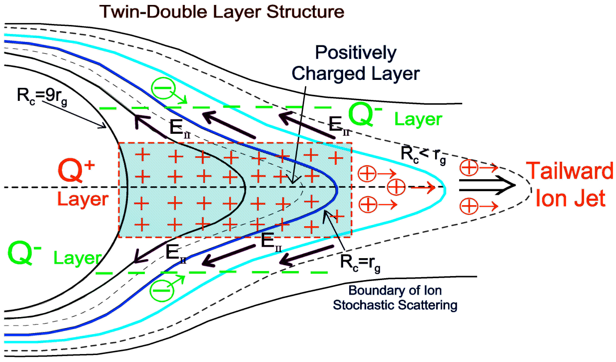

Fig. 1. The twin-DL system near the Earth. The demagnetized ions are concentrated at a central positively charged layer (the Q^+ layer) bounded on the north and south side by negatively charged layers (the Q^- layers). The electrons set up an oscillatory motion around the equatorial plane in order to achieve the ion neutralization. Electric fields along the magnetic field lines (E_{II}) are established, and "the whole machine" is able to launch, via strong electrostatic fields, tailward ion jets with high velocities. Under this condition a persistent ion electric current can flow through each double layer.

2.3. The ion jet production mechanism

The formation of the system of DLs implies that a net positive charge (the Q^+) is eventually accumulated in its central region. Schematic Fig. 2 shows the twin-DL structure; each DL is positioned symmetrically in respect to the neutral sheet plane (Z=0). In turn, we assume that the density from the semi-trapped ions in the very central region of plasma sheet is enough to produce ***significant repulsive electrostatic Coulomb forces***; then two major processes will be probably actuated. **First,** the portion of ions moving essentially vertically (upward or downward) will be reflected by the basically sunward or antisunward directed magnetic field lines forming two (dawn to dusk) surface currents in northern and southern magnetotail. These current sheets denoted by the current density J_y in Fig. 2 may correspond to the detected effect of cross-tail current bifurcation observed in TCSs [17]. **Second,** the ions at the edge of the accumulation region (where $R_c \cong r_g$) will be subjected to electrostatic forces moving them tailward within a channel where $R_c < r_g$. And this latter ion population may explain the observed ***tailward ion jets associated with substorms*** or pseudo-substorms in the Earth's magnetotail.

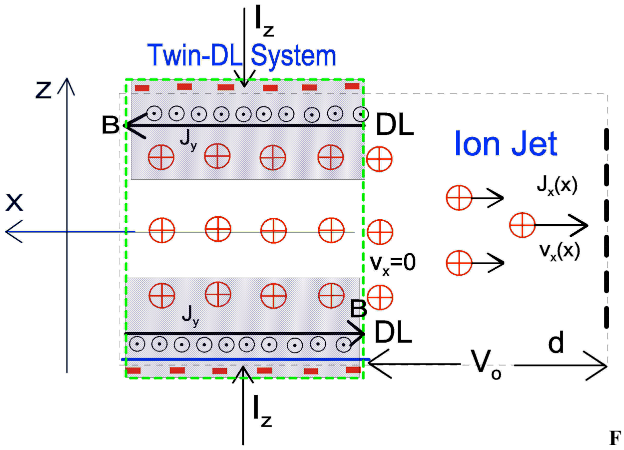

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Fig. 2. Schematic illustrating the twin-DL structure positioned symmetrically in respect to the neutral sheet plane (Z=0). The ions at the edge of the positively charged accumulation region will be subjected to electrostatic forces moving them tailward. The resulting ion jet is of great importance in substorms dynamics.

Once an ion jet is established, ***an ion current has to flow through each DL***, although the DL constitutes ***an electron current-free double layer***. Just at the tailward edge of the "positively charged cavity", the ion density could be appreciable large and the velocity zero. Far away tailward, one can assume that the ion velocity rapidly increases and the density drops. The force of repulsion makes the ions boiled off the positive space charge; we consider that they leave it with zero velocity. At that point the electric field E_x is zero, too. In the steady state the J_x current density (Fig. 2) is constant, independent of x:

$$J_x = \rho(x)u(x)$$

where the charge density ρ(x) is a positive quantity and the velocity u(x) is related to the electric field intensity E(x) by Newton's law of motion:

$$\frac{edV(x)}{dx} = m\frac{du(x)}{dx}$$

where m is the ion mass, V the potential drop and e =1,6x10^{-19} C. Further, based on an analysis similar to that leading to the Child-Langmuir law [18], we obtain

$$J_x = \frac{4\varepsilon_o}{9d^2}\sqrt{\frac{2e}{m}}V_o^{3/2}$$

That is, the current density J_x (measured in A/m^2), like the case in a space-charge limited vacuum diode, is proportional to the three-halves power of the V_o (being the potential drop-Φ_{DL} of each DL or the potential difference between the anode and the cathode in a diode) and is extended along the jet distance d; ***an apparently nonlinear relation.***

Certainly, the estimated current I_x originates from the twin-DL system: ***there is an ion inflow*** to the positively charged cavity from above and below and ***an ion outflow*** (the ion jet itself) from the right-hand edge of the Q^+ cavity. Thus, I_x=2I_z (Fig. 2). The cavity is assumed to be enveloped by an equipotential surface; the ions move at random within it.

Certainly the ion jet introduced so far corresponds to the "steady state conditions". An explosive phase of DLs is probable, as we shall see below, with much more dramatic effects, resulting in much higher plasma velocities and particle acceleration up to high energies. Since ***in the explosive phase the local small scale effects are coupled to those of large scale***, it is absolutely necessary to incorporate the DL in its whole natural environment. This effort is undertaken below using the overall magnetotail system as a usual electrical circuit.

2.4. The intra-magnetosphere dynamo

The Earth's night-side magnetosphere being a huge natural plasma laboratory in many aspects is similar with a simple circuit comprising an electrical generator (dynamo) in magnetotail, a gigantic current transmission line and a load over the ionosphere, at substorm times. Our major contribution in this subject is focussed on the physical process producing an earthward directed driving electric field E_d in the Earth's magnetotail and over the equatorial plane. A schematic of the overall proposed magnetosphere circuit, over the meridional plane (i.e., over the XZ plane) passing through midnight, is shown in Fig. 3. J_{II} and J_p correspond to a pair of upward/downward field-aligned current (FAC) sheets in the night sector and the Pedersen ionospheric current, respectively. We mention here that the earthward directed electric field, like the proposed E_d, is essentially the highly anticipated (for decades) electric field by Akasofu [19, 20].

We have already suggested that the twin-DL system has probably the capacity to produce strong tailward ion jets: it is supposed that the ions move within a channel characterized by $R_c< r_g$. The detailed analysis of the channel's properties goes beyond the scope of this work, only the issue of stability is briefly considered below. The electrons being magnetized for this situation (and therefore tied to the magnetic field lines) are left behind the ions being unmagnetized. ***The differential motion between ions and electrons creates both an earthward directed electric field and a tailward directed current. This is exactly the condition for a dynamo where J · E < 0, a result of charge separation created in the non-MHD fashion.*** This dynamo process is shown in Fig. 3 where the meridional current system (MCS) for a substorm is sketched; this is the so-called Boström's type II current system [21].

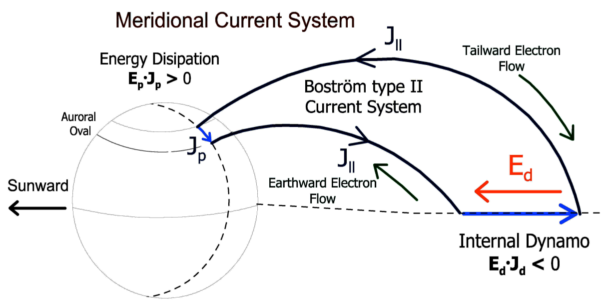

Fig. 3. The intra-magnetosphere dynamo related to the phenomenon of magnetospheric substorms over the meridional plane. The driving E_d-electric field on the magnetotail equatorial plane is produced by local charge decoupling inside and tailward of the twin-DL system. The Pedersen current J_p is essentially limited to the belt bounded by two latitudinal circles of 60° and 70° in the ionosphere altitudes; the ionosphere is here the load of the circuit. Boström type II current system, as it is suggested by Boström [21], is driven by the electric field E_d related to the electromotive force-emf; J_d is directed tailward and $E_c \cdot J_c < 0$, the dynamo condition.

Kamide [22] noted that the east-west ionospheric closure of the substorm current system, that is the substorm current wedge (SCW), which has long been regarded as a crucial element in substorms [23], was over emphasized by most substorm researchers. The dominant current system in terms of the total current strength should be the MCS because of its large east-west extent in spite of its weaker current density. The MCS strength could be as strong as 10 MA, as indicated by Ahn et al. [24] from constructing the global FAC distribution based on the KRM method [25]. Kamide [22] concluded that a new mechanism is needed to generate the MCS. Akasofu [20] re-examined three well-established substorm onset phenomena, namely, the sudden brightening of an auroral arc, the sudden growth of the westward electrojet, and the dipolarization. He noted that ionospheric closure of the MCS gives the main load to the substorm current system and must therefore be driven by a dynamo in the equatorial plasma sheet with an inward directed electric field. He concluded that the substorm current system is predominantly the MCS. Lui and Kamide [26], proposed a dynamo for the MCS to be a kinetic current disruption process such that dipolarization is achieved by magnetic field line slippage, thus producing the dynamo action of a tailward directed current with an earthward directed electric field. The electron convection speed associated with the field line slippage may be ~150 km/s [26]; the ion motion is considered to be largely unaffected by the field line slippage.

Our proposed dynamo mechanism is similarly based on the differential motion between ions and electrons like the mechanism of Lui, ***but the underline physical process is radically different.*** We suggest that the ions are ejected tailward from the twin-DL system; besides, satellites commonly observed velocities up to ~2000 km/s in magnetotail. The proposed here mechanism may be much more dynamic and potentially capable producing much higher amounts for the dynamo current.

2.5. Ion energization

When a DL (from the twin-DL system) is conducting a constant ion current, we can assume that the whole natural system is ***in a metastable state***; it permits the flow of an ion current that essentially is composed from the tailward propelled ions. Most importantly, after a long time the whole system may result to a catastrophic rearrangement. ***An explosive phase is anticipated*** whenever an abrupt current reduction occurs in the huge magnetosphere circuit associated with the substorm's current systems. During this phase the ions will be jetting with significantly increased velocities.

Every circuit which contains an inductance L is intrinsically explosive. The inductive energy $W_L = 1/2\ LI^2$ can be tapped at any point of the circuit. If we try to interrupt the current I, the inductance tends to supply its energy to the point of interruption where the power $P = I\Delta V$ is delivered (ΔV is the voltage over the point of interruption and I the current at this point). This means that most of the circuit energy may be released in a double layer, and if large, cause an explosion of the DL [1,2]. In general, if $J \cdot E < 0$ (i.e., at the ion jet region) we have a generator transferring plasma energy into the circuit; if $J \cdot E > 0$, we have a motor transferring circuit energy into kinetic energy of the plasma. In Fig. 4 we show the generator with the symbol where the arrow is parallel to I and the motor with the symbol where the arrow is antiparallel to I. The circuit contains a resistance R which dissipates energy $RI^2/2$ into heat over the ionosphere. The inductance L is related to the FACs and the transmission line connecting the DL with the ionosphere. The adopted electrical symbol for a double layer, when represented in an electrical circuit is **─DL─**. If there is a net current present, then the DL is oriented with the base of the L in line with direction of current. Certainly the shown circuit is not a new concept; Boström has shown that an equivalent magnetic substorm circuit is a way of presenting the substorm model even from 1974. The innovative idea in this work is considered to be the jetting ions due to DLs and the physical mechanism that potentially builds up the DLs.

An electrotechnical circuit like Fig. 4 consists essentially of metal wires. Obviously in cosmic plasma problems most or all the circuit elements are distributed over cosmic distances. However, our purpose here is not to carry out a detailed study but to get a general survey of energy transport in the Earth's magnetosphere; this circuit approach is a first approximation to the problem.

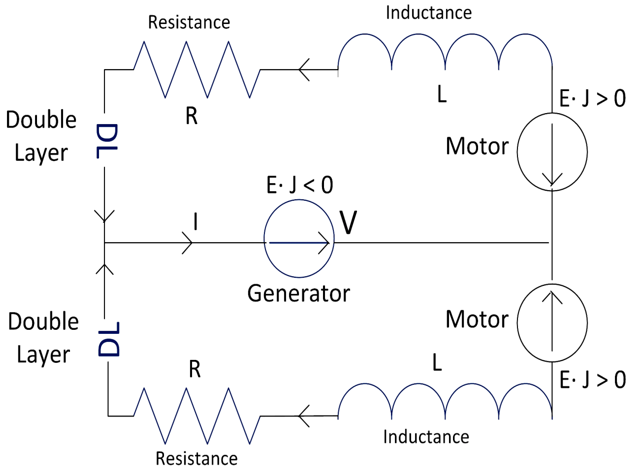

Fig. 4. This is a first approach circuit for the Earth's night-side magnetosphere during substorms. It incorporates both the plasma sheet and the ionosphere processes. The twin-DL structure launches the tailward ion jet, a process corresponding essentially to the dynamo (generator) symbol. The dynamo results from the differential motion between ions and electrons which creates both an earthward directed electric field and a tailward directed current, the I.

Whenever the current changes with time, a self-induced emf appears in any inductor. The magnitude of the direct current has no influence on the magnitude of the induced emf; only the rate of change of the current counts. If the current in our circuit is abruptly reduced the induced voltage V across the DL will have an exceptional high value, since $V = LdI/dt$. ***This potential drop may produce the populations of hundreds of keV detected in the Earth's magnetotail.*** Besides, a major signature associated with such a mechanism might be the detection of ions and electrons accelerated to opposite directions. Therefore, a space probe would probably detect, at any place tailward of the activated source, abundance in energetic ion fluxes, at the same time, with dramatic energetic electron flux decreases. ***This process converts magnetic energy into particle energy without the need to create an X-type magnetic neutral line.***

3. A case study

It is particularly important to look at the DL evolution, as it is probably captured in satellite measurements. We select a case study where Geotail was positioned at X=-30.6 R_E and ***remained at the very central plasma sheet*** throughout the whole interval presented in Fig. 5. The plotted interval corresponds to a distinct substorm event which is studied elsewhere from another point of view [13]. The substorm onset is manifested here by the Bear Island (BJN) ground station (with geographic latitude 74.50^0 and longitude 19.20^0) magnetogram from the IMAGE array showing a reduction of ~450 nT (first panel). The tailward plasma flow was initiated at ~22:40 UT (fifth panel). The energetic proton differential fluxes from 58 to 77 keV (channel P2 from the EPIC experiment) with the highest resolution time are shown at the second panel trace; the angular distributions (not shown here) clearly manifest their tailward streaming character. The energetic electron integral fluxes with energies greater than 38 keV (ED1 channel) are shown in the third panel.

During the DL explosive phase the ~60 keV energetic proton fluxes dramatically increase; after ~22:46 UT the fluxes enhance by more than one order of magnitude. In contrast, the energetic electrons clearly show an "electron dropout". The electrons within the twin-DL system are obviously accelerated and escaped earthward along the magnetic field lines; it seems that they essentially precipitate over the ionosphere and participate in the auroral phenomenon. Conversely, the ions are correspondingly accelerated toward the positively charged ion cavity of the twin-DL system; in turn, the ions (because of their large gyroradii) move in random and escape tailward. Moreover, since the electron population is abruptly released earthward, it is anticipated that a significant fraction of it will rebound back mirrored over the ionosphere. Actually, we may infer that the returned electrons (from the first rebound) overshoot the ambient (unaffected) population; it seems that around ~22:46:15 UT the already accelerated electrons stream tailward.

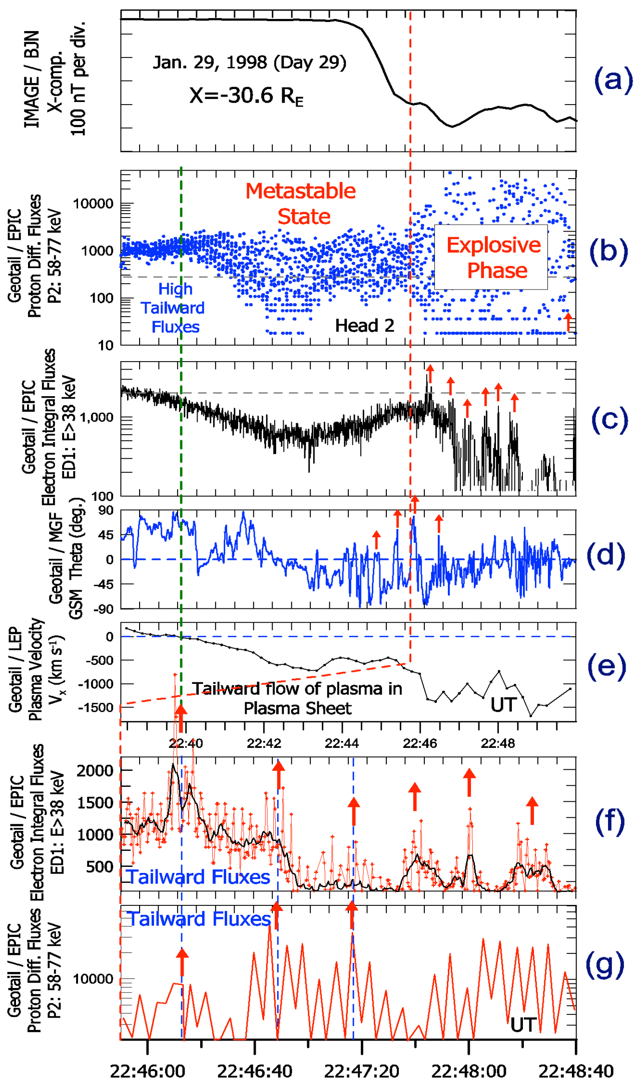

Fig. 5. From top to bottom: (a) The BJN ground station magnetogram from the IMAGE array; (b) the highest resolution differential fluxes of the 58-77 keV protons;(c) the highest resolution integral fluxes for the greater than 38 keV electrons;(d) the polar angle (theta) of the magnetic field (in degrees); (e) the antisunward ion velocity of plasma (in kms^{-1});(f) a close-up of energetic electron fluxes showing their pulsating character; (g) a close-up of energetic proton fluxes. The explosive phase of proton fluxes is associated with an energetic electron dropout.

Furthermore, in our case study, ***it seems that the system of DLs develops a resonance frequency***. The DL is built up and decomposed every ~25 s, in a periodic fashion. The latter would be supported by four-fold observations: (a) the electron fluxes being greater than 38 keV show six quasi-periodic and distinct peak fluxes marked with arrows along the third and sixth panel traces; (b) the ~60 keV proton fluxes show three peak fluxes occurring simultaneously and corresponding to those of electrons; (c) the magnetic field theta angle, around the onset time of the DL explosive phase, clearly shows a few variation cycles with the same periodicity, and (d) the tailward plasma velocity clearly increases for the three first peaked electron and proton fluxes. After the DL explosion, the pre-accumulated electrons within the twin-DL system will oscillate between the DL and the ionosphere. Indeed, we compute that the electrons, with thermal energy ~750 eV, need ~24 s to travel along the two-hop trip of ~60 R_E; these values characterize our case.

We would like to further stress that the acceleration source obviously has acted over the ion and electron populations in a diametrically opposite manner. The "DL explosive phase" ***is characterized by an overwhelming enhancement of energetic protons and a profound depletion of energetic electrons***. Naturally, the impartial observer can assume the existence of an electrostatic field accelerating ions and electrons toward opposite directions. Therefore, the pre-existing populations are modulated, as expected, by the electrostatic electric fields developed during the explosive phase of DLs. In contrast, a hypothetic X-type reconnection source must produce electrons and ions toward the same direction simultaneously.

4. Discussion

4.1. The excess of positive charge in the "ion cavity" between the DLs

The surplus of positive charge (developed in the central layer of the whole layered structure of DLs, the amount being denoted by Q^+) may be comparable to the initial charge Q_o. If the ion density is n=0.6 cm^{-3} and $Q^+=Q_o$, and if the affected volume is 2000 km (thickness of plasma sheet)x10000 km (extent along the X-axis)x5000 km, then $Q^+ \cong 10$ MC. This estimated amount of charge can be regarded as sufficiently powerful to drive the FACs involved in substorms.

4.2. The ion jet and the "ion capsule"

As soon as the tailward ion jet is emerged, an "ion cloud" moves tailward forming a propagation front. Progressively, as the velocity steadily increases (and observationally this is always the case) new ions pile up at the propagation front. In this way, the tailward directed gradient of ion density will produce (along the propagation front) ***an intense current like the I_{xy} one sketched in Fig. 6a.*** Besides, this current inevitably introduces an additional process that further strengthens the "initial seed B_z field". A satellite passing through the I_{xy}-current will detect the $+B_z/-B_z$ signature (identified in MFR-like structures). ***The jetting ions are moving horizontally (tailward) and the neutralizing electrons perpendicularly (i.e., orthogonally) to them and along the magnetic field lines***. The electrons probably oscillate back and forth crossing the neutral sheet. ***The fast antisunward moving ions momentarily attract the electrons and set up their "vertical oscillatory motions".*** In this way one can infer that the existence of an ion jet is something feasible within the plasma sheet. Especially electrons rush along the magnetic field lines to neutralize the newly arriving ions at the propagation front, where the charge is locally peaked and consequently the incoming electrons form intense FACs. Most importantly, the electrons moving in curved magnetic field lines, and achieving their maximum velocities crossing the neutral sheet, will finally undergo eastward drift; the local cross-tail current strengthens and the B_z deviations further intensify. Eventually all the jet ions are prevented to cross the positive-B_z barrier. ***The production of an exceptionally intense and locally restricted B_z component of magnetic field, at the heart of plasma sheet, may be the ultimate process to approach the puzzle of the MFR-like structures.***

Now, we switch to the meridional-XZ plane in the Earth's magnetotail. Somewhere tailward of the jetting ions, the plasma naturally convects earthward being driven by the $\mathbf{E_y}$x$\mathbf{B_z}$ drift. Therefore, there is a site where the plasma velocity V_x has to be zero; the plasma velocity (as measured *in situ* by a satellite) seems to change sign. Whenever a satellite encounters an ion jet, we anticipate a magnetic field topology as schematically drawn in Fig. 6b with the reddish-solid line. The satellite (S/C) seems to cross the "ion capsule region", an area termed by Sarafopoulos [15]. Apparently, the curvature radius of the capsule's magnetic field is now much larger than the r_g: This holds true since the capsule ions (being the jetting ions) are encapsulated by a magnetic field being the superposition of the ambient field B_{zo} plus the (cross-tail diamagnetic) current dependent perturbation ΔB_z. If the dawn-to-dusk capsule current is I_y (Fig. 6b), then on its tailward side the magnetic field has to be $B_{zo}+\Delta B_z$ and on its earthward side it has to be $B_{zo}-\Delta B_z$. Consequently, a satellite traversing the ion capsule (and moving earthward, as indicated by the dashed-black line) should detect a bipolar north-then-south magnetic field signature; a signature of great importance being one of the main morphological features associated with ***an MFR-like structure*** (i.e., the capsule itself). Certainly, the capsule ions undergo a neutralization process via FACs flowing along the magnetic field lines that encompass the jetting ions; a B_y deviation is produced at the transition time from $+B_z$ to $-B_z$ (Fig. 6b). Therefore, ***the whole structure of currents is stable***. Although the homoparallel FACs are mutually attracted, however, they do not collapse because there is an additional repulsive force on each of them from the ion jet current.

4.3. Is there an inconsistency in the reconnection model?

It is already pointed out that in this work we intend to introduce a new concept rather than to revise or criticize the existing reconnection model. However, the latter does not mean that we ignore what Alfvén [1, 2] categorically stressed by writing "that anyone who uses the merging concepts states by implication that no double layers exist". Below, we briefly discuss another significant aspect related to this work effort.

It is generally admitted that when somebody selects and evaluates events on the basis of a few criteria, in the same selection process, not so infrequently (and perhaps inevitably) he or she has already pre-determined a conclusion. In particular, it is statistically established [27], on the basis of 73 MFR events, that the MFRs embedded in tailward plasma flows exhibit the magnetic field bipolar north-then-south signature. In turn, this inference led to the scenario of two X-type reconnection lines working at both edges of the supposed flux rope. One plausible question: Is it possible to characterize an MFR embedded in tailward plasma flow by a south-then-north magnetic field signature?

Obviously, it is an unanticipated signature occurring in the reverse order (in contrast to what we learned by the statistics). Would a reconnection model explain such a feature?

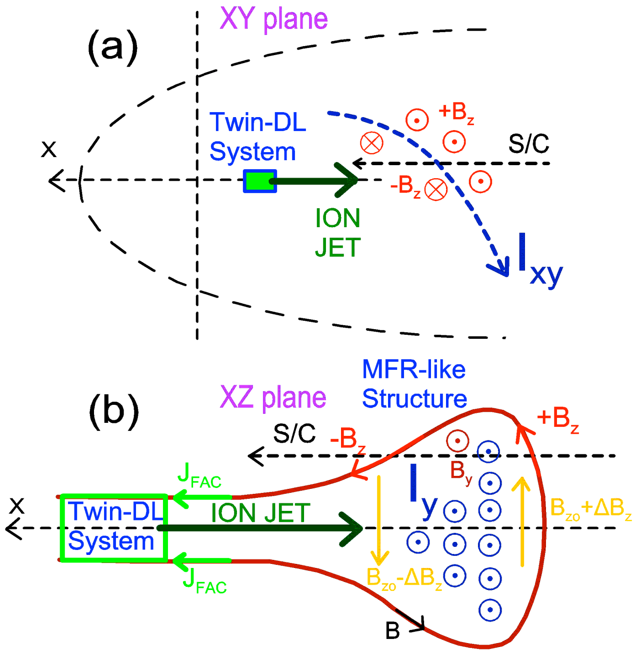

Fig. 6. (a) An equatorial cross-section of the Earth's magnetotail (XY plane) illustrating the anticipated geometric track for the diamagnetic current at the propagation front of the jetting ions tailward from the twin-DL system. A satellite (S/C) crossing the current will identify a bipolar signature (north-then-south) for the B_z component. (b) A meridional cross-section of magnetotail showing the MFR-like structure formed tailward of the twin-DL system. The diamagnetic current I_y produces the local perturbations ΔB_z which are added to the ambient magnetic field component B_{zo}. The superposition increases the curvature radius in the cavity termed as "ion capsule"; apparently $R_c >> r_g$ at the right-hand side of cavity.

Actually, in Fig. 7, we show an indicative MFR-like structure morphologically identified by the B_y core and the bipolar signature of B_z: the plasma velocity is $V_x \approx$ -600 kms^{-1} (sixth panel), the core of the supposed MFR is $B_y \approx$ -15 nT (third panel) and the B_z trace clearly shows at first a negative (about -15 nT) and later a positive (about +15 nT) deflection (fourth panel). The whole structure occurred in the very central plasma sheet, given that the $B_x \approx 0$ nT (second panel). It is underlined that the ratio of $B_z/B_{total} \cong 1$, at the places supposed to be dominated by the helical-tubular field of rope. ***In the context of this work***, a probable interpretation may be as follows: Whenever the tailward ion velocity increases, a diamagnetic current at the jet front will produce a bipolar positive-then-negative signature passing by the satellite. Hypothetically, if three distinct and successive tailward ion velocity increases are produced, then we have to observe (as we presently predict, and we are going to treat it of in the near future) three distinct (cross-tail) diamagnetic currents passing by the satellite position and creating sequential bipolar signatures associated with an intense B_y deviation at any time B_z is zero.

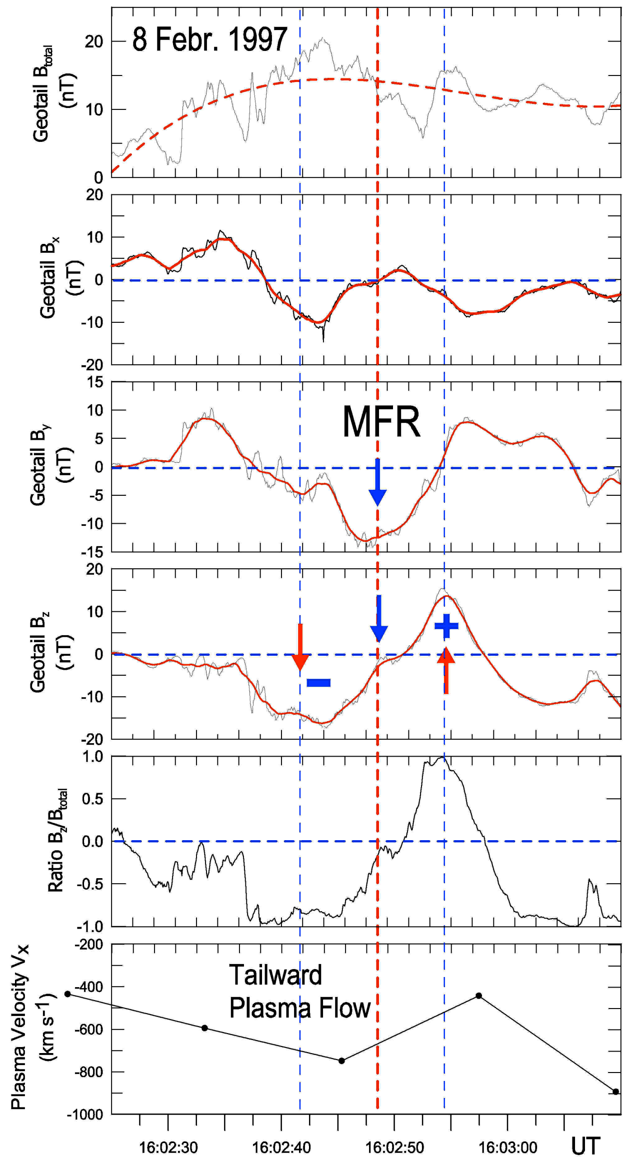

Fig. 7. An MFR-like structure morphologically identified by the magnetic field B_y-core and the bipolar signature of B_z. The whole structure occurred in the very central plasma sheet ($B_x \approx 0$ nT, second panel). The core of the supposed MFR B_y is -15 nT (third panel) and the B_z trace clearly shows a bipolar -/+ signature (fourth panel). The plasma velocity is $V_x \approx$ -600 kms^{-1} (sixth panel). It is worth noticing that the ratio B_z/B_{total} is ~1, where the B_z shows extreme values. The dashed-red line trace in the top panel is the third order polynomial fitting of the total B.

4.4. Pulsating aurora and the dual-DL system

Electrons participating in the dual-DL structure and contributing to its neutralization may finally produce one more observable feature visible by naked eye and occurring during substorms: the pulsating aurora. The term "pulsating aurora" characterizes the repetitive modulation in the auroral luminosity. The period of pulsation is typically of the order of 1-30 s. The intensity variations can be repetitive, quasi-periodic or occasionally periodic [28] and variations can last sometimes only for a few pulses but sometimes even for hours. The electrons, moving adiabatically and threading the layered structure in the twin-DL structure, are supposedly oscillating around the positive cavity charge, the Q^+ region.

The Q^+ constitutes a surplus of ion population; the neutralizing electrons must have their maximum density around the same place, too. That is, the electrons "are packed" close to the equatorial plane and if the system of DLs collapses, the electrons will be released toward the ionosphere. If the DL-ionosphere distance is 15 R_E and the thermal electron energy is 300-1000 eV, then the electrons mirrored over the ionosphere will come back in 10-18 s. If the collapse occurs in a repetitive manner, then a resonance between the dual-DL structure and the electrons moving forth and back between DL and ionosphere is potentially feasible; the involved periodicity will be T_e=10-18 s. Even if a definite collapse (in the twin-DL system) occurs, a few repetitive cycles of precipitating electrons might be produced. ***Periodic energetic electron fluxes are already reported*** in the analyzed event of Fig. 5. In conclusion, pulsating auroras may be a visible manifestation of the precipitating electrons accumulated close to the equatorial plane within the DLs.

The PiC-type geomagnetic pulsations (ULF waves) are related to pulsating auroras as the conductivity changes driven by the precipitation pulsations which modulate both the ionospheric currents and FACs [29, 30].

Pulsating auroras are usually observed at morning local times; a trend that may be in accordance with the fact that the oscillating electrons within the dual-DL system will drift dawnward, too. Pulsating (electron) auroras are anticorrelated with proton emissions, that is proton auroras [31]. The latter matches very well with our suggestion; the surplus population of DL-ions essentially will flow tailward, whereas the surplus of electron population will precipitate over the ionosphere.

4.5. An approximate estimate for the ion jet velocity

If an ion is trying to access the positively charged cavity, it will be forced to decelerate. ***Under steady state conditions***, an ion will gain entry into the Q^+ layer, if its thermal velocity is enough to balance the deceleration that it experiences within the double layer region. Thus, one can argue that if an ion gains entry into the Q^+ layer (moving along the magnetic field line), then another ion will be pushed away along the Sun-Earth X-axis. Therefore, ***the ion jet velocity would be approximately equal to the thermal velocity of plasma***; we could write

$$u_{jet} = \sqrt{\frac{2nkT}{m}} = 440\ W^{1/2}$$

That is, u_{jet} is the ion velocity in kms^{-1}, while the W is set to keV. For plasma of 3 keV, u_{jet} = 700 kms^{-1}; for plasma of 6 keV, u_{jet} = 980 kms^{-1} and, for 10 keV u_{jet} = 1250 kms^{-1}. Values that are commonly observed in tailward plasma flows associated with substorms. If the DL performs a transition to its explosive mode, then the plasma velocity must rapidly increase.

The usual expression for the Debye length, that is

$$\lambda_D = (\varepsilon_o kT / 2n_o e^2)^{1/2}$$

is produced in the limit $q\Phi_{(r)} << kT$, where $\Phi_{(r)}$ is the electric potential at position r. We have assumed a large scale perturbation, where the Q^+ represents a huge amount of charge and it can be expected that λ_D is not too small compared to the L being the length-scale of the process under investigation; the above relation is probably not the only valid one.

Conclusions

The investigations followed the principle that "every inductive circuit carrying a current is intrinsically explosive" [1, 2]. This fundamental principle is practically applied, for instance, to the specific electric circuits related to fluorescent lamps or to an ordinary vehicle driven by a combustion engine. In the latter case, an ignition coil is a main circuit component that transforms the vehicle's battery voltage, for example 12V, up to 15000 - 30000 Volts to supply the spark plugs that finally serve for the ignition of the engine. Consequently, according to the proposed circuit model, a twin-DL entity, with strong DLs, is able to produce, in its explosive mode, ion jets with very high velocities (i.e., ~2000 kms^{-1}) and highly accelerated particles (in the range of hundreds of keV).

If the proposed concept is further applied and tested with respect to the Earth's magnetosphere, then ***it turns out to be applicable to the solar flares*** as well. The DL is treated as part of a circuit which delivers current I and releases energy at a rate $P = I\Delta V$, where ΔV is the Voltage generated by the DL. Neither the DLs nor the described circuit can be derived in an obvious manner from any established magnetofluid models related to plasma phenomena. Thus, an essential and promising step ahead is performed by identifying a net current flow (extended to a few multiples of R_E) in the very central plasma sheet region. ***For the first time, a model based on a large scale current is proposed, where the current does not propagate along the magnetic field lines, but orthogonally to them.*** In this way, the magnetosphere phenomena can be estimated with a more stable model.

An additional useful spin-off is the definition of the current closure path for the current that flows through an MFR, which is obviously a different approach in comparison (for instance) to that of Kivelson et al. [32]. According to the present perception, the ion jet current is related to the intra-magnetosphere emf applied over the meridional current system of Boström's type II (for a substorm). The same current is essentially producing the MFR's core current.

Presently it is assumed that the twin-DL entity is created near the Earth, mainly within a radius of 8-16 times R_E. Obviously, deeper inside the tail it would produce earthward directed jets as well.

It should be underlined that the overall proposed scheme for the twin-DL entity in addition to the coupled MFR-shaped structure (on its tailward side), morphologically, is not a subject matter deviating essentially from that represented by the NENL model associated with the coupled X-type and O-type lines. However, ***the approaches are radically different as far as the underline physical mechanism is concerned. The twin-DL entity is functioning close to the ion inertial length***, whereas in collisionless X-type reconnection the formation of "the electron diffusion region" is required. If the first entity is actually in operation, then it is not recommended to focus intensively on any small-scale phenomena (that is, "the electron diffusion region") ***and, in particular, not with regard to future multi-satellite missions.***

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